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GODDARD

IN-90-CR

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P-38

FINAL REPORT

ON

NASA, GSFC, GRANT : NAG 5 1497

TITLE: RADIATION-INDUCED ROTATION OF SMALL CELESTIAL BODIES

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and

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DATE: March 17, 1992

Attachment: Five pages of technical data from MVM Electronics Inc., the builder
of the modulator, on the Laser Intensity Modulator.

(NASA-CR-190085) RADIATION-INDUCED ROTATION
OF SMALL CELESTIAL BODIES Final Report
(Florida Inst. of Tech.) 38 p CSCL 03B

N92-20071

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INTRODUCTION

In 1985, we embarked upon a program contracted by the Air Force Office of Scientific Research (AFOSR) to study the use of aggregates of small particles for defense applications. This program started in July, 1985, and ended in February under AFOSR contract # F49620-85-C-0117. It was also preceded by a DOD grant AFOSR # 84-0212, which was awarded by the Defense University Instrumentation Program (DURIP). This grant was used to build a state of the art Laser-Particle Dynamics Facility at the University of Florida, Gainesville, Florida. The total cost of both programs was approximately \$650K. The Principal Investigator (Dr. N.Y. Misconi) joined the Faculty of Florida Institute of Technology's (FIT) Space Research Institute (SRI) in February of 1989. The Laser-Particle Dynamics Facility was also moved from the University of Florida at Gainesville, to FIT in Melbourne, Florida, as part of a collaborative agreement between the two universities. The Facility is now located in the new Applied Research Laboratory Building at FIT.

This experiment uses a technique known as Laser-Particle Levitation, first introduced by Ashkin and Dziedzic (1971). The idea is to overcome the weight of a solid particle 20 to 90 microns in size by the photon pressure from a focused argon CW laser, thus simulating space conditions when levitation is done in vacuum. Details of this technique are stated later in this document. We used this technique to levitate pure (absorption Coefficient $5 \times 10^{-4} \text{ cm}^{-1}$) silica spheres in the focused laser beam and measured the resulting light scattering pattern to enhance our understanding of the light scattering process.

Results from light scattering measurements of laser-levitated spheres were published in Applied Optics Journal, May 20th issue of 1991. These results when compared to a theoretical Mie light scattering curve showed excellent agreement. Also numerous reports on the experiment were submitted to AFOSR including a final report.

The main purpose of the experiment is to study the rotation of particles in a simulated space environment. The combination of both a high vacuum and optical/laser levitation to negate the effects of Earth's gravity, simulate the space environment. The rotation mechanism under study is known as the "Windmill Effect," which is a spin mechanism that suggests that the interaction of the photon field from a star with the surface irregularities of cosmic dust will cause them to spin due to the imbalance in the directionality of the scattered photons which necessitates a non-zero angular momentum. This conclusion is based on the random nature of the orientations of the sites of surface irregularities.

This Windmill spin mechanism was first suggested by Opik (1936), and later studied by Paddack (1969, 1973, 1975), Misconi (1976a), and Ratcliff, Misconi, and Paddack, (1980). It is non-statistical spin mechanism, since it depends on the orientations of the surface irregularities of the dust particles. Figure 1, illustrates an ideal windmill turbine (Paddack, 1973).

Our general purpose is to study the behavior of particles in orbits around the Earth, both natural and man-made, as well as interplanetary and circumstellar particles. Other dynamical forces will also be under study, which include the optical forces that confine the particle in the beam, the force needed for bringing the particle to its equilibrium position in the absence of air, and other dynamical behavior that the particles may exhibit in vacuum.

To meet these objectives, we have constructed an apparatus designed to allow optical levitation in a vacuum. The experimental design was based partially upon papers by Ashkin and Dziedzic (1977), and has seen considerable improvement on their original design.

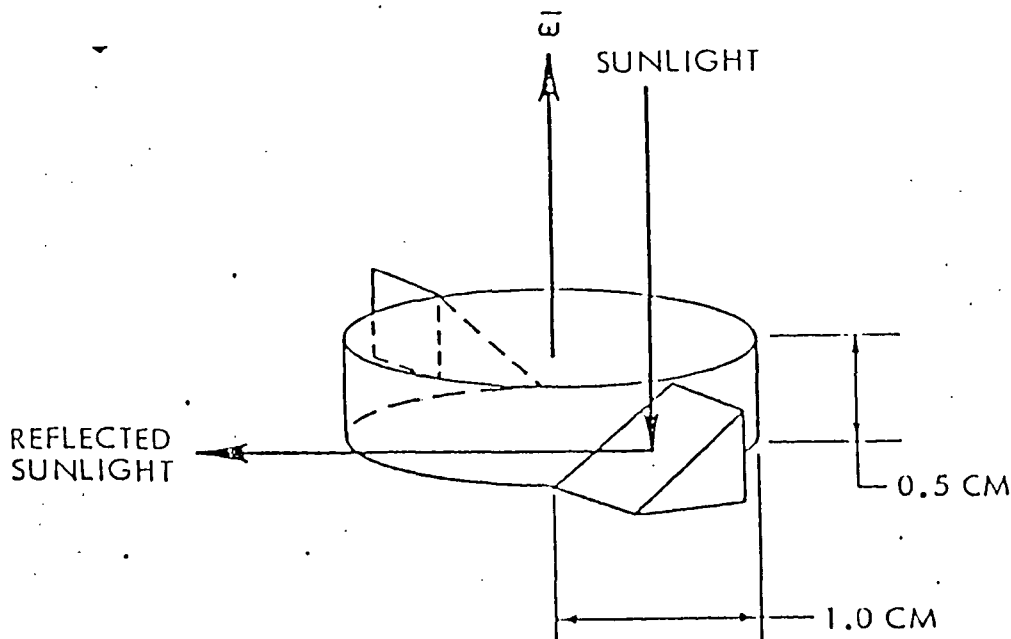


Fig. 1. An ideal Windmill Turbine (Paddack, 1973).

THE CONCEPT OF LASER-PARTICLE LEVITATION

In our apparatus, the levitated particle is supported by a three dimensional optical trap formed above the focus of a lens by the laser beam. The radiation incident upon the particle serves the dual purpose of both levitating the particle and providing the radiation which accelerates the particle's rotation. Here, momentum is transferred to a particle in the process of scattering radiation. The momentum transfer balances the weight of the particle (levitation), and also provides confinement of the particle in the transverse direction (Ashkin and Dziedzic, 1971). The transverse confinement is illustrated in Figure 2.

The fact that the particle is a transparent sphere and that the profile of the laser beam is Gaussian (TEM₀₀ mode) creates this transverse confinement. The higher intensity near the maximum of the beam creates a stronger restoring force that pushes the particle always toward the maximum of the beam.

Ashkin (1971) measured this transverse confining force and found it to be one half the force needed to balance the weight of the particle (1/2 g). Ratcliff, Misconi and Paddack (1980) found a similar strength for the transverse force in an earlier (1979) laser-particle levitation experiment at Goddard Space Flight Center (GSFC), where they also developed for the first time a three beam optical confinement bottle to trap irregular particles by splitting the argon beam into two antiparallel beams plus a vertical beam. With our present apparatus, we have achieved levitation of particles of up to 95 μ m in size.

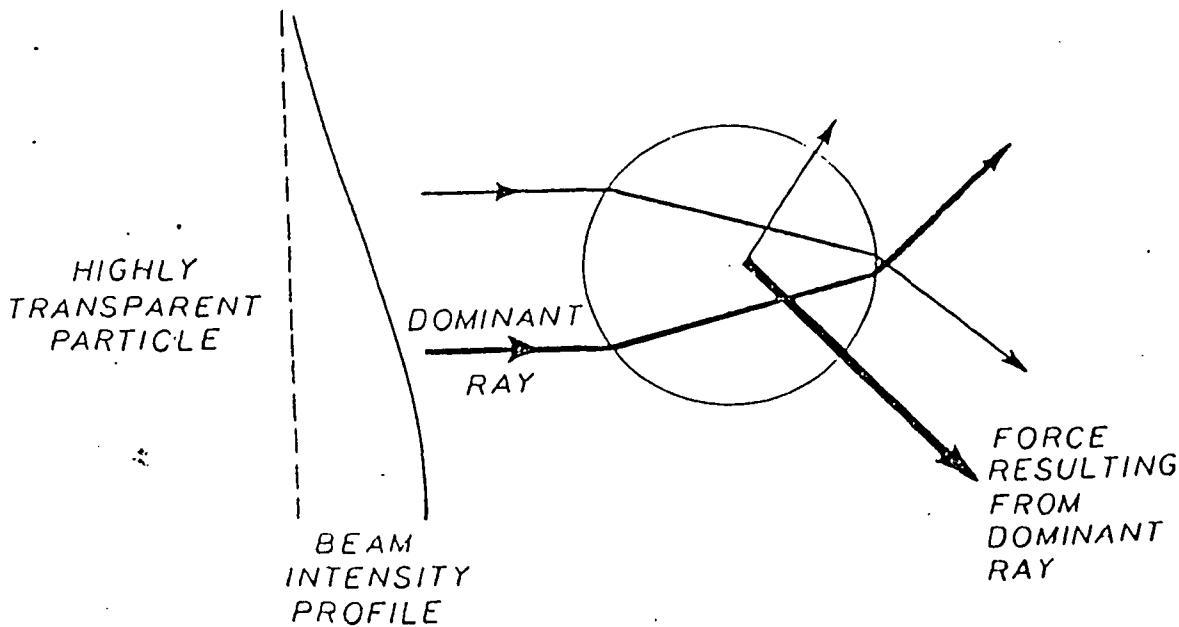


Figure 2. Momentum transfer and the resulting transverse confinement of a transparent sphere in a Gaussian beam.

Rotational Bursting due to the "Windmill Effect"

Paddack investigated this mechanism theoretically and experimentally. The following is the result of his investigation:

In order to measure the angular acceleration from a windmill type spin Paddack (1970) started with defining the torque (N) on the particle,

$$N = P_r A L a \quad (1)$$

where P_r is the radiation pressure, a is the cross sectional area of the particle intercepting the radiation, L is the "effective moment arm" of the rotation, and A is the Albedo of the particle. Paddack (1973) attempted to deduce a value for L by devising a hydrodynamic analogy of a windmill type rotation. He dropped randomly selected stones through a column of water and observed that each stone acquired a given spin rate about a given axis. Most important was the fact that the chosen axis and spin rate was reproducible for each of the sample rocks upon repeated falls. The average of all these samples suggested that the torque experienced by the rocks corresponded to an effective moment arm 5×10^{-4} times the maximum linear dimension of the sample. Sekanina (1979) recognizes the importance of determining the magnitude of the asymmetry factor (effective moment arm) that gives rise to particle spin and eventual fragmentation through the windmill effect that will explain the synchronic bands in comets (see section earlier).

Misconi (1976) has shown through model calculations that, due to the solar radiation induced "Windmill Mechanism," dust particles produced by asteroidal collisions can not spiral past 1.2 AU heliocentric distance. This is so because rotational bursting will reduce the particles' sizes to where radiation pressure becomes the dominant force. Consequently, they will be expelled from the solar system. This occurs before the particles' semimajor axes decrease to 1.2 AU from the P-R effect. This result leaves the cometary origin as the predominant source of the dust inside the Earth's orbit.

Paddack and Rhee (1975) investigated the effect of magnetic damping on the spin rate of a spinning charged dust particles and found that the damping is only significant for metallic particles and can be ignored for tektites and other non-metallic particles.

The angular momentum generated is from the laser photon field bouncing off the irregularities at the surface of the particle. **Since the irregular sites on the surface are random in their distribution, angular momentum will never be zero.** Furthermore, the particle will spin the fastest at a specific orientation of the particle that has the highest differential irregularity.

The rotational equation of motion of the particle is:

$$I \frac{d\theta}{dt} = P_r A L a \quad (2)$$

where I is the moment of inertia and θ is the angular speed in rad/sec. By integrating equation (2) and assuming that the particle starts from rest, we get

$$\omega = \frac{P_r}{2\pi I} A L a t \quad (3)$$

where ω is the angular speed in **rotations per second**. For a sphere, $I = 2/5 ms^2$, where m is the mass of the particle, and s is the radius of the spherical particle, and $L = 2sl$, where l is then the effective moment arm expressed as a fraction of the maximum length of the particle. Substituting for I , L , and a we can rewrite eq. (3) for spherical particles:

$$\omega = \frac{0.596 A P_r}{s^2 \delta} l t \quad (4)$$

where δ is the specific density of the particle. For particles in the solar system at any heliocentric distance (r) the radiation pressure is

$$P_r = \frac{E_0}{r^2 c}$$

where E_0 is the solar constant (1.36×10^6 ergs/cm² sec) and c is the speed of light. The spin rate in rot/sec then can be written as:

$$\omega = \frac{0.596 E_0}{s^2 r^2 c \delta} A l t \quad (5)$$

$$\omega = \frac{0.596 E_0}{s^2 r^2 c \delta} A / t \quad (5)$$

or

$$\omega = \frac{0.27 \times 10^{-4}}{s^2 r^2 \delta c} A / t \quad (6)$$

The rotation rate needed to burst the dust particle was derived by Misconi (1976b) to be: equating the centripital force/unit area to the tensile strength of the spherical particle:

$$\frac{F_c}{area} = \frac{m s \omega^2}{2\pi s^2} \approx T$$

and

$$\omega_b = \frac{1}{2\pi s} \sqrt{\frac{T}{\delta}} \quad (7)$$

By combining equation (2) and (7), we get:

$$\frac{0.27 \times 10^{-4}}{s^2 r^2 \delta c} A / t \geq \frac{1}{2\pi s} \sqrt{\frac{T}{\delta}} \quad (8)$$

When this condition is met the particles burst.

INSTRUMENTAL DETAILS AND OPERATIONS

This section deals with the instrumental details and operations for particle laser-levitation in vacuum.

A- Vacuum Chamber Design

The vacuum chamber has dimensions (cylindrical, 5 inches in diameter, 4.5 inches high) comparable to the scattering chamber used in our earlier experiments. This allows the easy interchange of the vacuum chamber with the scattering chamber, and the utilization of the same illumination and viewing systems, as well as the same data acquisition apparatus.

A translation/rotation vacuum mechanical feedthru in the top plate supports the particle launching plate. This was necessary to allow the movement of the launching plate out of the optical path, thus avoiding the possibility that particles remaining on the plate might distort the illumination of the levitated particle. In practice, it was found that it was relatively easy to lower the launching plate to the bottom of the chamber, and then rotate it out of the beam quickly without interrupting the illumination long enough to cause the particle to drop. A pair of electrical feedthrus in the top plate carry the voltage to the piezo-electric launching mechanism.

In order to select a particle for levitation, it is necessary to translate the launching plate in the x-y plane perpendicular to the laser illumination beam. Rather than place an x-y translation system within the vacuum, we translate the entire vacuum chamber on a large load supporting precision x-y translation stage.

B- Vacuum System

In order to achieve vacuums below 10^{-7} Torr, the vacuum system consists of a mechanical forepump and a turbo-molecular high vacuum pump. Thermocouple and Ion vacuum gauges are installed in the vacuum lines coupling the turbo-molecular pump to the chamber. A flexible coupling allows the x-y translation of the vacuum chamber for particle selection. A right-angle cross-section allows control of the pumping rate, while (when fully open) avoiding restriction in the maximum vacuum achievable. Figure 3 and 4 show the components of the vacuum system as well as the vacuum chamber.

When a vacuum is pulled, the flexible coupling contracts. This puts a strain on the mounting of the vacuum chamber. The viewing system (especially the height servo system) is very sensitive to small angle tilts. In order to avoid displacing the vacuum chamber, the turbo-molecular pump is mounted on a precision translation slide which allows it to move closer to the chamber.

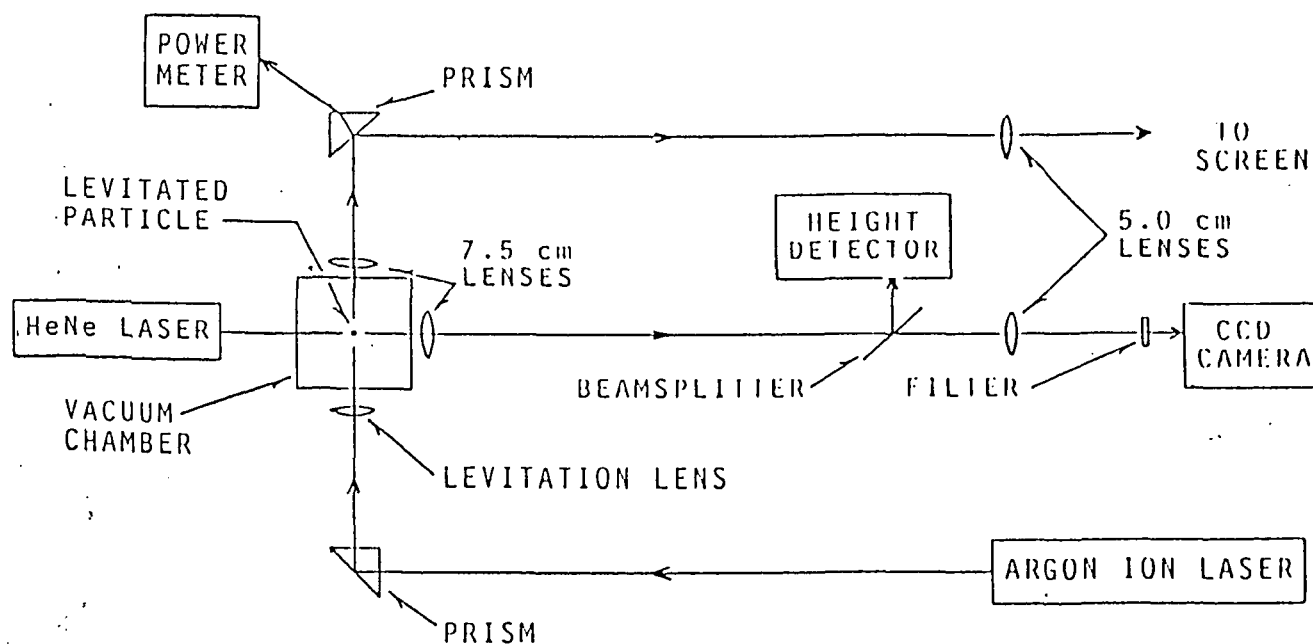


Figure 3. A diagram of the optical system.

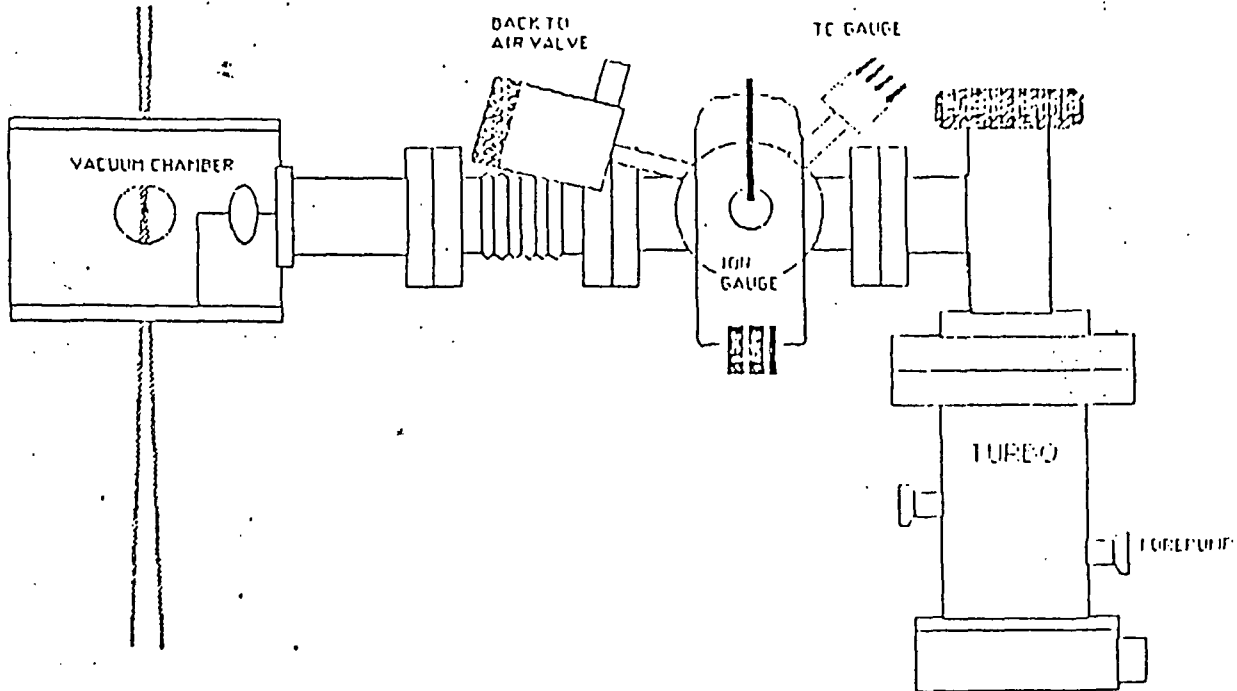


Figure 4. A schematic diagram of the vacuum system, consisting of a Turbo-molecular pump, forepump, and associated mechanical parts.

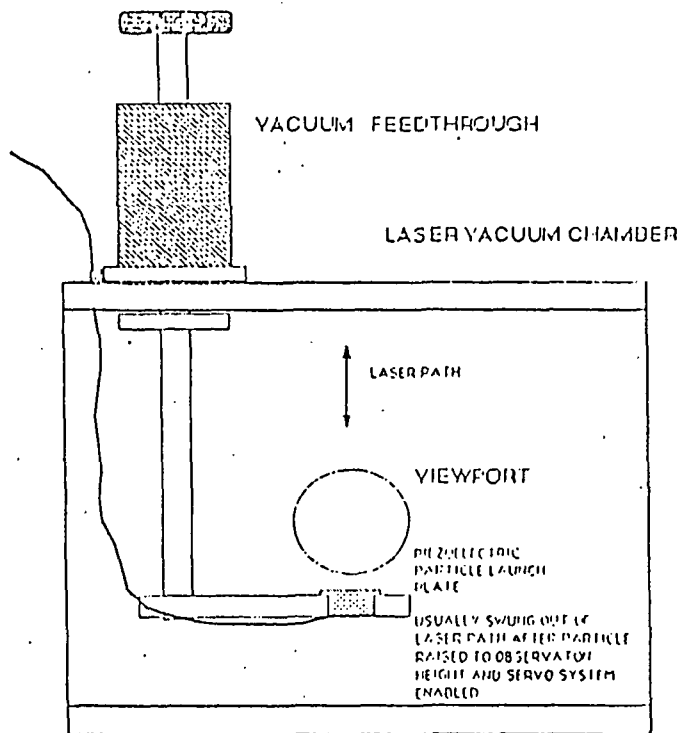


Figure 5. A schematic diagram of the vacuum chamber and the launching plate.

A small back-to-air valve vents the chamber between vacuum runs. Early in the experiment, we observed that a fog appeared within the vacuum chamber when a vacuum run was initiated. This fog was clearly visible in the laser illumination beam, and a considerable reduction in transmitted light resulted from scattering in the fog. Consequently, a dry Nitrogen supply was used to fill the chamber between vacuum runs.

C- Particle Imaging System:

In order to investigate the dynamics of a vacuum-levitated particle, we devised a video imaging system which provides relatively high time-resolution images of the levitated particle. This is an extension of the imaging system used in earlier experiments. A high-resolution CCD camera was interfaced to the data acquisition computer. This camera was placed so as to image the vertical (0 degree) and side views of the particle. A high speed frame grabber allowed digital storage of 8 sequential video frames at intervals of 1/60th of a second. The camera allowed re-scanning of " " of the frame 4 times per "frame" to allow a time resolution (for " frame images) of 1/240th of a second.

For viewing of the side image (90 degrees) a small red laser (He-Ne) was mounted as an illumination source. Thus the green 90 degree image from the levitation laser could be directed to the height servo detector while the red image was directed to the video system.

D- Height Servo System:

When a small particle is levitated in air, stability is provided by the damping effect of the air. This facilitates "trapping" of the particle in the laser illumination beam, and damps out perturbation caused by radiometric forces (due to particle surface heating) on the particle. In a vacuum this damping is lacking, and some sort of external stabilization becomes necessary. We imaged the 90 degree image of the particle on a split photodiode to provide feedback on the height of the particle. The computer system processed the height data and provided an error rate damped feedback signal to modulate the laser power.

The natural frequency of a levitated particle in the size range used in our research is a few tens of hertz. Since the power supply for the laser has provision for external modulation at frequencies of more than 100 hertz, we modulate the laser power supply to provide feedback.

E- Previous Test Results:

The height servo sensor works well at atmospheric pressure. An oscillating particle "freezes" when the servo system is activated, and remains at essentially a constant height, even as the position of the focus of the laser beam is moved up and down. However, as the pressure in the chamber was reduced, several problems develop.

First, the particle was observed to "drift" downward steadily as the vacuum was pulled. Initially this was ascribed to the development of the "fog" mentioned above. However, even after dry Nitrogen was used as the working gas, eliminating the fog, the downward drift continued to be observed. Eventually the particle was pulled below the range of the height servo detector and it immediately dropped. After considerable experimentation with changes in the vacuum pumping rate, location of the vacuum port on the chamber, etc., it was concluded that the flow of gas from the chamber was the source of the problem. The servo system equations were modified to include an integral term which reflected continuous displacement of the particle from the desired height. This was successful, allowing rapid pumping without any significant downward displacement of the particle. The servo system increased the laser power by as much as a factor of 3 over the

power necessary to levitate at 1 atmosphere while in the process of holding the height constant during pumping.

In spite of maintenance of constant height during pumping, after the pressure in the chamber dropped below approximately 50 Torr, the particle always became increasingly unstable, oscillating in the vertical direction with increasing amplitude and frequency. It was clear that the height servo system was unable to stabilize the particle as the pressure became low. While the response of the laser power supply was sufficient for small changes in brightness, the high amplitude modulation necessary for stabilization in the 50 Torr region could not be achieved by this method.

We were able to locate another means of modulating the laser beam at a high enough frequency to damp out these oscillations. An electro-optical modulator was obtained on loan which was rated at 10 watts maximum power (barely enough as we had observed power excursions exceeding 4 watts when stabilizing the downward drift of the particle during pumping). This modulator allowed a beam up to 2.5 mm to pass safely and unobstructed. Unfortunately, although the laser beam in use was specified as 1.6 mm diameter, it was - in fact - somewhat more than 3 mm in diameter. Careful realignment of the laser was unsuccessful in reducing the beam diameter.

Numerous attempts were made to levitate the particle initially in vacuum. Unfortunately, the particle generally leaves the launching plate with some sideward motion which takes it through the optical trap above the laser focus. In the absence of damping, the particle does not remain in the trap. Although we managed to keep particles in the trap for short periods in vacuum (less than 2 seconds), we did not manage to hold a particle stable for a period long enough to investigate its dynamic properties.

We stress here that stable levitation in vacuum was performed successfully by Ashkin and Dziedzic (1977). We are not trying to prove it can be done, we merely want to adapt it to our more complicated apparatus that is geared to study the rotation of the particle.

Progress Achieved via this Grant

At the start of this funded research, we carried out an instrumental search for the best method to construct the servo system. Our earlier intentions were concentrated on obtaining an electro-optical modulator from Oriel Corporation, and we did experiment with one such device called "Stable Lase". However, the width of our argon laser beam was too high to efficiently modulate the laser beam power.

After further research, we decided that an acoustical modulator is better suited for this purpose. We then contracted a local company under the name of MVM Electronics and had numerous discussions with its owner Dr. Munhar L. Shah, a well known instrumental physicist who designed and built for us an acoustical-optical laser modulator. He built this device specifically to suit the purpose of our experiment. This device was built and tested, and now integrated with our argon laser. Dr. John Oliver (Co-I) made several trips from the University of Florida at Gainesville to our laboratory at Melbourne, Florida to help in the design of the acoustical modulator, and prepare the apparatus for the new phase of the experiment.

We succeeded in integrating this device to our experiment and expect complete success in delivering the kind of modulation necessary for our project. The specifications and other details of this device are included in the Appendix of this Final Report. We also acquired an analog to digital board for our Dell Computer that runs the experiment. As far as the remaining objectives of this project, we were unable to do much progress considering the time and effort that went into preparing our experiment to accommodate the new device. The amount of funds (15K) that we received for this phase of the project, did not allow us to progress further.

The good news are that our experiment is now ready to perform the research outlined in the previous pages, once a sponsor is found. Unfortunately our proposal to NASA's Geophysics and Planetary Geology Program was denied funding for reasons that are not fully clear to us. A similar proposal was submitted to the National Science Foundation's Solar System Program in January 1991. The reviewers gave it very high marks, and the Discipline Scientist, Dr. Vernon Pankonin, recommended funding. However, their budget was not able to fund the proposal.

In any case, we have been asked to submit our proposal again to the same NASA Program, and we intend to submit it the April 1st deadline. We are now in the process of defining a space experiment as a follow on to this ground-based experiment to be conducted inside the Gas-Grain Simulation Facility (GGSF) that will fly on board of the Space Station Freedom. The PI is currently in touch with Dr. Judith Huntington (NASA Ames Research Center), Project Manager of the GGSF, to incorporate our experiment in the design of this Facility in order to do further research that will complement our ground-based experiment.

We are very grateful that this grant enabled us to bring our experiment to full readiness for doing the measurements that is called for by this project. We look forward to receive the kind of financial support (80K a year for two years) that is needed to perform this experiment and achieve its goals.

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APPENDIX

MVM ELECTRONICS, INC.

115 Hickory Street, Suite 102 Melbourne, FL 32904 (407) 728-1957

**OPERATION OF LASER POWER CONTROLLER
MODEL MCL050S**

The MCL050S is an acousto-optic laser power control system. It consists of an acousto-optic modulator device and a driver. The acousto-optic modulator diffracts light by creating strain grating in Tellurium Dioxide crystalline material in response to a 50 MHz RF signal. When the RF signal is present a part of an optical beam power passing through the modulator material diffracts into a first order beam and the remaining undiffracted beam called zero order beam is reduced in power. The optical aperture of the modulator is 3.5 mm dia. The beam must pass slightly away from the transducer surface to avoid scattering from the edge.

The diffracted light fraction follows $[\sin\{KP\}]^{1/2}$ ² dependance on the RF power, P, where K as is a constant. The modulator is coated with a broad band anti-reflection coating with center wavelength at 514.5 nm. One can use the undiffracted light beam and adjust its intensity by subtracting diffracted light intensity by RF power or use the diffracted beam and adjust its intensity by the RF power. In the first case the optical intensity decreases with increasing RF power while in the other case it is reversed.

The driver consists of an on-board oscillator, a mixer, and an amplifier. The crystal oscillator operates at 50 MHz and the mixer accepts 0-1 Volt input to provide RF power nearly linear to the input voltage. The amplifier has about 30 dB gain and provides approximately 1 Watt RF power at the maximum level. The power supply to the driver is included so that it can be operated from 115 VAC line outlet. The driver dissipates about 20 Watts through ventilating holes, therefore, it must not be obstructed.

The specifications of the system, and the test data are provided herewith.



MVM ELECTRONICS, INC.

115 Hickory Street, Suite 102
Melbourne, FL 32904
(407) 728-1957

Laser Intensity Controller Specifications

Model Number MLC050-S

o	Optical wavelenght	488-514.5	nm
o	Beam diameter	3.5	mm max.
o	Beam distortion	± 10 %	max
o	Optical Aperture	5X3.5	mm (L) Xmm (H)
o	Optical loss	4 % @ 514.5 nm	max
o	Power Control	to 50 %	min
o	Size	50X50X50	mm3 max
o	Polarization	Verticle	(preferred)
o	Power	2 A @28 VDC	max
o	Rejected light angle	5	mr min
o	Control Signal	0-1 V	nominal
o	Deviation from Linearity	± 20 %	max
o	Light Intensity	10	W max

This is a complete system consisting of an optical modulator and an electronic driver.

Price	\$3000
Delivery	8-10 weeks ARO
Terms	30 days Net
FOB	Melbourne, FL
Warranty	90 days for material and workmanship.

Signed:

Date:

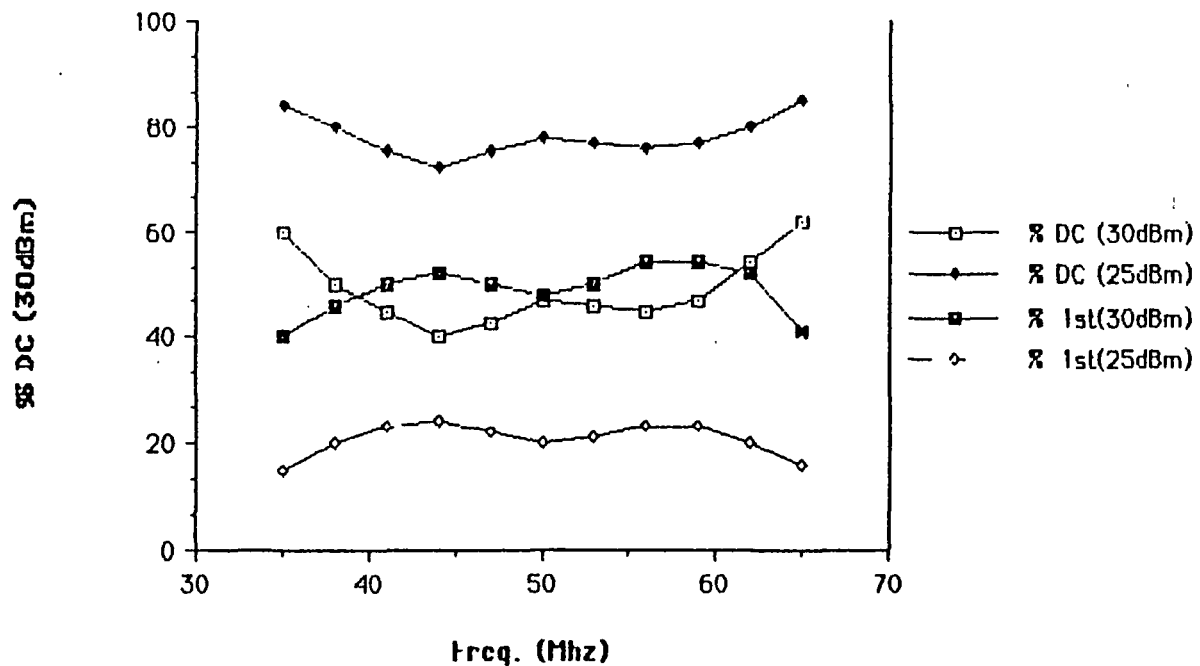
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P.O. # 21868

Freq. (Mhz) % DC (30dBm) % DC (25dBm) % 1st(30dBm) % 1st(25dBm)

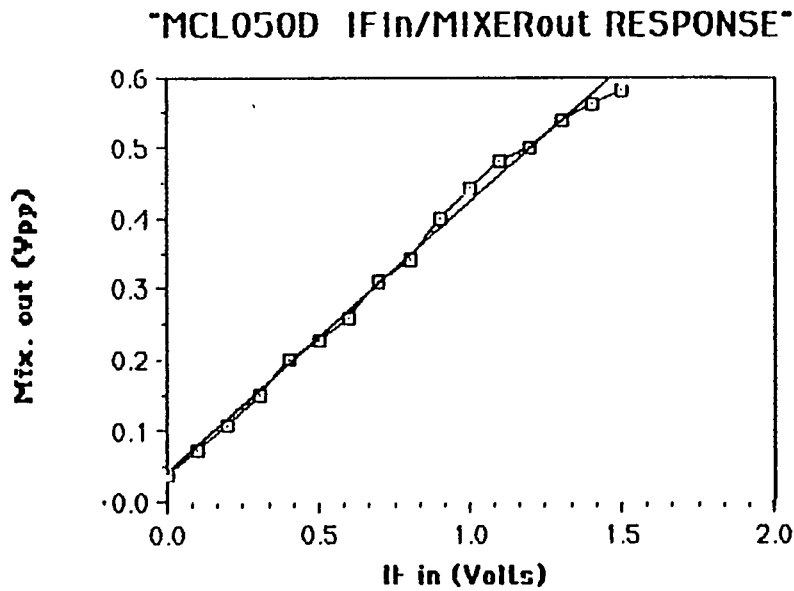
1	35.000	60.000	84.000	40.000	15.000
2	38.000	50.000	80.000	46.000	20.000
3	41.000	45.000	75.000	50.000	23.000
4	44.000	40.000	72.000	52.000	24.000
5	47.000	43.000	75.000	50.000	22.000
6	50.000	47.000	78.000	48.000	20.000
7	53.000	46.000	77.000	50.000	21.000
8	56.000	45.000	76.000	54.000	23.000
9	59.000	47.000	77.000	54.000	23.000
10	62.000	54.000	80.000	52.000	20.000
11	65.000	62.000	85.000	41.000	16.000

"MCL050D/7-91 Diffraction Efficiency"



IF in (Volts) Mix. out (Vpp)

1	0.000	0.040
2	0.100	0.075
3	0.200	0.110
4	0.300	0.150
5	0.400	0.200
6	0.500	0.230
7	0.600	0.260
8	0.700	0.310
9	0.800	0.340
10	0.900	0.400
11	1.000	0.440
12	1.100	0.480
13	1.200	0.500
14	1.300	0.540
15	1.400	0.560
16	1.500	0.580



Volt in vs. % Loss, Transmitted at 632.8 nm

